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Tracking and Sensor Fusion Issues in the Tactical Land Environment

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ABSTRACT

This preliminary report discusses sensor fusion in the Tactical Land environment, describing several examples and identifying key issues related to the automated estimation of target characteristics including location, velocity and identity using disparate sensors or information sources.

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Contents

Figures

Tables

Glossary

C2	Command and Control
CAESAR	Coalition Aerial Surveillance and Reconnaissance
CDL	Common Data Link
CEC	Cooperative Engagement Capability
ES	Electronic Surveillance
FLIR	Forward-Looking Infra-Red
GMTI	Ground Moving Target Indication
GPS	Global Positioning System
HMI	Human-Machine Interface
HMMWV	High Mobility, Multi-Purpose Wheeled Vehicle
I2	Image Intensifier
IDM	Improved Data Modem
IMM	Interacting Multiple Model
IP	Internet Protocol
IR	Infra-Red
IRST	Infra-Red Search and Track
ISAR	Inverse Synthetic Aperture Radar
JDL	Joint Directors of Laboratories
Joint STARS	Joint Surveillance Target Attack Radar System
MOE	Measure of Effectiveness
MOFE	Measure of Force Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organisation
PDA	Personal Digital Assistant
SAR	Synthetic Aperture Radar
TADIL	Tactical Digital Information Link
UAV	Unmanned Aerial Vehicle
UGS	Unattended Ground Sensors
VMF	Variable Message Format
VS-IMM	Variable Structure Interacting Multiple Model
VS-IMMPF	Variable Structure Interacting Multiple Model Particle Filter

1 Introduction

The Tracking and Sensor Fusion Group of the Intelligence, Surveillance and Reconnaissance Division has made a preliminary review of tracking and sensor fusion techniques and technologies at the Object Assessment level of sensor fusion that may be applicable to the Tactical Land environment. In this context, the purpose of tracking and sensor fusion is to translate reports from sensors and other information sources into higher level information regarding the environment, in particular tracks that represent the *existence*, *kinematic state* and *identity* of man-made platforms, such as ground vehicles, aircraft and ships.

Of prime importance to the Tactical Land environment is focal area surveillance and reconnaissance, such as that provided by electro-optical or radar sensors mounted on small airborne platforms, and local, ground-based surveillance using, for example, ground vehicle based sensors, unattended ground sensors, portable surveillance radars and/or infra-red (IR) systems, and observation posts. Integrating these elements to provide a practical and interoperable system that addresses the needs of the users at their various levels is a complex issue [Asenstorfer, Cox & Wilksch 2004], some aspects of which are discussed in this report.

A useful taxonomy of sensor fusion is that of the Joint Directors of Laboratories (JDL), which divides sensor fusion into several levels [Steinberg & Bowman 2001]. Level 0 denotes 'sub-object data assessment', or sensor signal processing; for example, taking a signal representing a radar return from the environment and deciding whether or not an object with a high radar cross section has been detected. Level 1 is 'object assessment', such as updating track data with sensor reports, or inferring track identification information based on prior knowledge of air lanes and timetables. Level 2 is 'situation assessment', which is the estimation of target information based on perceived entity relationships. Level 3 is 'impact assessment', which seeks to determine and predict the effects resulting from the estimated circumstances. Level 4 is 'process refinement', a controlling mechanism that provides feedback at all levels, including the control of sensors. Whilst sensor fusion at all of these levels is relevant to the Tactical Land environment, this report focuses on issues at JDL Level 1. For information regarding sensor fusion at higher levels, in the broader context of Australia's interests, see [Oxenham, Percival, Price & Lambert 2003].

The network-centric warfare paradigm is useful in the context of modern warfighting, suggesting that sensors, command and control, and shooters be intimately connected via sensor, engagement and information grids, so as to achieve information superiority [Alberts, Garstka & Stein 1999, Warner, Finclaire & Pacey 2001]. In this way, all participants can, in principle, (i) have full access to situation awareness information, (ii) take command of any aspect of any situation, and (iii) utilise any weapon. This permits an optimal management of capability to meet any circumstances, such as the automatic assignment of weapons to targets. However, this model does not map comfortably across to the Tactical Land domain due to the degree of autonomy that is required by tactical commanders [Warner et al. 2001]. Instead, Warner et al. [2001] propose the paradigm of information layers at the tactical, operational and strategic levels. Commanders that operate at each of these levels could utilise software that is common, but is appropriately tuned to manage the different types of applicable information. In this way, commanders would have "the right data at the right time". For example, tactical displays could show raw data, whereas higher levels would only show the fused products. This paradigm should dramatically improve upon the situation where "up to 80 percent of a staff officer's time can be spent conducting manual processing" [Hogan 1998].

Imagery is especially valuable in the Tactical Land environment, providing target detection and identification for surveillance, reconnaissance and strike applications, and for battle damage assessment following ground attack. The provision of imagery to tactical users is difficult, owing to the management of the data and the large bandwidths required for communicating the information. Situation awareness in the Tactical Land environment is, in general, complicated by constraints on sensors, such as obstructions limiting their coverage, the similarity between targets of interest and the surrounding environment (owing to high clutter levels and possibly low target speeds), restrictions on equipment, such as size and weight, the fast tempo of operations, and the dispersal and separation of units [Warner et al. 2001].

Sensors, platforms and communications links of value to the Tactical Land environment include:

- ground-based radar;
- unattended ground sensors (UGS);
- Infra-Red Search and Track (IRST);
- Forward-Looking Infra-Red (FLIR);
- image intensifiers (I2);
- synthetic aperture radar (SAR), that is, airborne or spaceborne ground imaging radar;
- inverse synthetic aperture radar (ISAR), that is, target imaging radar;
- observation posts providing manual reports;
- electronic surveillance (ES);
- satellite imagery;
- manned reconnaissance imaging systems, e.g., RF-111, reconnaissance / attack helicopter (RAH);
- soldiers;
- Unmanned Vehicles (including Unmanned Aerial Vehicles, UAVs), which may be large (such as Global Hawk) or small (soldier launched) and, possibly, expendable;
- ground vehicles;
- voice channels;
- Improved Data Modem (IDM), which provides real time, tactical data communications via on-board radios [Asenstorfer et al. 2004, Chapter 3];
- Variable Message Format (VMF), a member of the J-series family of data links (along with Link-16 and Link-22), is designed to be used by combat units at different organisational levels to exchange data [Logicon, Inc. 1997];
- Common Data Link (CDL), which provides data communications typically between surveillance aircraft and ground stations [Asenstorfer et al. 2004, Chapter 5].

Clearly, there are many combinations of sensors, platforms, communications channels and users, with associated issues that need to be considered when compiling and distributing a situation awareness picture.

The rest of this report is structured as follows. Section 2 provides pertinent examples of sensor fusion for improving situation awareness in the Tactical Land environment, Section 3 discusses some of the issues associated with distributed sensor fusion, and Section 4 describes an approach for accommodating reports from manual observers into an automated tracking process.

2 Tactical Land Sensor Fusion Examples

The principles of tracking and sensor fusion and their application to the tactical land environment are best communicated through examples. Those illustrated here are the fusion of plot data from radar and infra-red search and track systems, the fusion of imagery from image intensifier and forward looking infra-red systems, means by which the battlespace may be automated, and the usage of specialised tracking processes, particularly improving kinematic tracking performance by utilising a priori terrain information.

2.1 Radar / IRST Fusion

Radar and infra-red search and track (IRST) sensors are complementary in many respects, and the combination is well suited to surveillance over complex terrain, including the littoral. Applications include the early detection of anti-ship missiles and as a portable surveillance device [Tenix 2001]. A brief comparison of radar and IRST sensors follows.

Radars are active sensors, providing a means for illuminating a target so that it may be detected via the returned radiation [Skolnik 1990]. They are able to measure the target's relative location in range and azimuth, and possibly elevation, depending on the type of antenna used. Range accuracy is typically very high, in the order of tens of metres, but angular accuracy may only be within a degree or so, depending on the type and size of the antenna relative to the wavelength of the emitted radiation. The update rate may be fairly low with a rotating antenna, typically in the order of several seconds, or many times a second with an electronically steerable phased array antenna, depending on the relative priority of the task in comparison with other radar tasking. In order to reduce the number of returns from targets other than those of interest, Doppler filters may be employed to mask returns from stationary objects. However, returns from moving objects in the environment, such as trees and ocean waves, may compete with the signals from low speed ground vehicles, so that simple Doppler filtering may be inadequate. Radar emissions may be detectable by electronic surveillance systems, and radars are subject to jamming and spoofing by electronic attack.

In comparison, IRSTs are passive sensors, relying on receiving infra-red radiation emitted by the target. Being imaging sensors, they are able to measure a target's azimuth and elevation to high accuracy, but have no means of directly measuring range. This may instead be estimated, as discussed below. IRSTs may have a very high update rate, particularly in the case of a system that stares in a fixed direction. Areas of the image may be masked out to reduce false detections, which

may occur from bright objects including clouds, and reflections of the sun from the sea surface, for example.

The combination of radars and IRSTs provides the best characteristics of both systems — three dimensional target localisation, a high update rate, and a higher probability of target detection. Since the mechanisms that cause false alarms are different for each sensor, if one sensor suffers a reduced level of performance in a particular region, the other sensor may be unaffected. However, there are difficulties associated with fusion, including the problem of sensor registration (Section 3.2).

Legg, Kieu & Gordon [2004] evaluated Cramér-Rao lower variance bounds (CRLBs) for a fused radar and IRST system. CRLBs represent the greatest accuracy that may be achieved by any tracker given a set of measurements and a target motion model, and may be used as a frame of reference when the performance of a tracking system is being evaluated. The results illustrate that angle-only information, as obtained by an IRST, is inadequate for estimating a target's location in three dimensions while the target travels in a straight line. When a manoeuvre takes place, more information is available, and range uncertainties may be reduced. In addition, where a target is detected by both sensors, the track accuracy is higher than when the target is detected by only one sensor.

2.2 Image Intensifier / Forward-Looking Infra-Red Fusion

Another example of data fusion with complementary sensors is a helmet-mounted imaging system for helicopter pilots, drivers of Army vehicles and soldiers that uses Image Intensifiers (I2) and Forward-Looking Infra-Red (FLIR) sensors [Reago 2004]. Each of these sensors is appropriate in some circumstances, but has limitations in others. FLIR sensors exhibit a high contrast between the background and targets of interest, such as people, animals and roads. They are also able to see through smoke and dust. However, they may have a low resolution, and IR systems fail where the scene has a uniform temperature.

In comparison, optical I2 systems have a high dynamic range and high resolution, but have low contrast between targets and the background. However, they cannot penetrate smoke or dust, and may require active illumination under conditions of low ambient light levels. Image fusion seeks to overcome the shortcomings of these systems by providing imagery to the user that utilises the advantages of both types of sensor.

As an example, Figure 1 shows the separate and fused output from FLIR and I2 sensors used in a helicopter pilotage scenario [Reago 2004]. The FLIR image shows high contrast between the road and surrounding terrain, and the I2 image shows lights and shadows. The central, fused image shows all these features.

As another example, Figure 2 shows the output from an imaging system mounted in a High Mobility, Multi-Purpose Wheeled Vehicle (HMMWV) [Reago 2004]. Figure 2(c) shows the output when the sensors' images, shown in (a) and (b), are summed (following histogram equalisation to maximise contrast, and applying an appropriate weighting), and (d) shows the output from a more sophisticated data fusion algorithm (although no details are provided in the reference). The fused images show the pedestrians and foliage features superimposed on the background lighting that is visible in the I2 image. Clearly, even summing images (a) and (b), once they are correctly registered, provides a significant improvement over the separate usage of either.

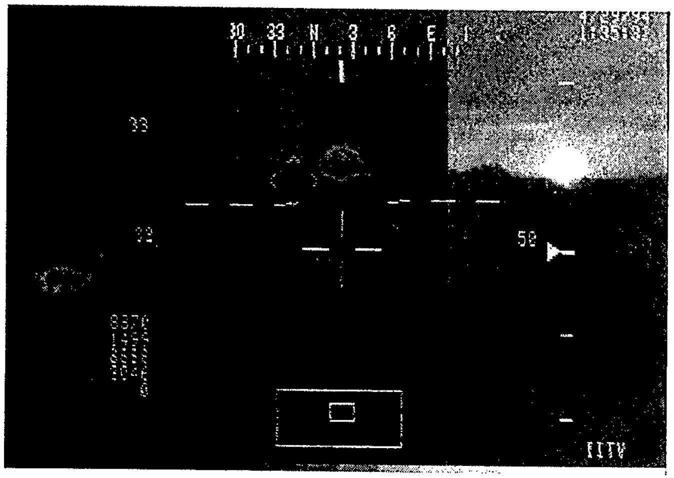
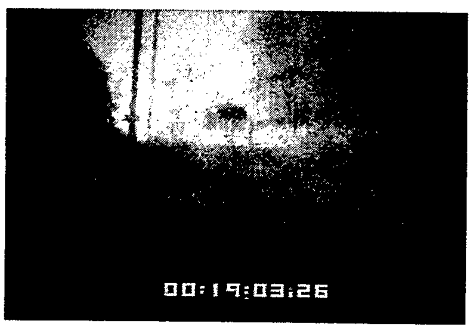


Figure 1: Helicopter pilotage I2/FLIR imagery example. Left: FLIR, right: I2, centre: fused image.



(a) Image intensifier output.

(b) FLIR output.

(c) Additive output.

(d) Feature fused output.

Figure 2: Gravel road scene example of image intensifier and FLIR fusion.

Problems with image fusion include sensor registration, minimising the latency in the motion of the sensors, and the difficulty in assessing the fused results.

2.3 Battlespace Automation and Unmanned Vehicles

There are numerous tasks that would benefit from automation in the Tactical Land environment, including those shown in Table 1[1]. Many of them involve processing and sharing sensor data. In general, automation may be appropriate for activities that are dangerous or require a continued effort over a long period, but do not require complex decision making. Accordingly, those identified as being of greatest importance do not involve replacing soldiers in a battlefield environment, contrary to popular expectation, but assist humans, and reduce the number of support personnel. A prime example of this is in logistics, where automated vehicles could be used to deliver ammunition and other supplies to soldiers, who would be involved in more complex activities. This would allow people to be assigned to tasks that require the talents of a human, and prevent the exposure of lives to unnecessary risk. The direct replacement of soldiers with automata is not likely in the foreseeable future. Automation may take many forms, one of which is a network of distributed sensors.

Cooperative sensor networks have the potential to increase the engagement tempo and tactical effectiveness of future land warfighters by integrating disparate sensors and weapons [Chong & Kumar 2003, Sciacca, Cullen & McCleery 2001]. An example of a system that distributes and fuses multisensor data is the US Navy's Cooperative Engagement Capability (CEC) [Alberts et al. 1999], which utilises a dedicated data distribution system. As an alternative approach, Sciacca et al. [2001] describe a sensor network that aims to make the most efficient use of available communications bandwidth, avoiding the overhead of having each sensor broadcast all information to other participants. This requires a sensor scheduler that decides which sensor or information source will contribute what information to the network at any time, based on the usefulness of the information that is anticipated from each sensor. A request is sent to the selected sensor or information source, which then provides the appropriate measurement or information update. Data sources can include radar, electronic surveillance, acoustic sensors, infra-red and visible imaging systems, seismic sensors and proximity sensors. This concept could be extended to support the

[1] This discussion is based on a session chaired by LTCOL Jason Thomas, Automation of the Battlespace Workshop, 6th May 2004.

Table 1: Unmanned vehicle applications in the land environment.

Mission	Application	Reason
protect†	area security, counter mine	personnel/material
inform	communications relay	long duration
detect/find†	point reconnaissance	safety risk
sustain†	resupply	manpower savings
shape	deception	break enemy will
strike	battle damage assessment	safety risk

†Those missions considered to have greatest importance by LTCOL Thomas.

control of sensor systems, such as the flight paths of UAVs to make best use of their sensors, and allow for weapons, which may be assigned to targets by manual or automated processes.

Owing to the miniaturisation of electronic systems, it is now conceivable to implement a network of tiny, low cost sensors that could communicate wirelessly and report to other systems via an interface. One company conducting research in this area is Dust Networks [Dust Networks 2004]. In principle, these sensing devices could be easily scattered over an area, and sense temperature, pressure, sound, or other environmental phenomena. They would organise their communications network automatically, implicitly accommodating an expansion of the network with additional sensors, and provide redundancy in the event of damage or power failure. Potential military applications for such networks include the provision of situation awareness, such as via acoustic sensor systems for ocean surveillance, acoustic tracking of ground vehicles, and monitoring infrastructure for potential threats such as terrorism [Chong & Kumar 2003]. Problems with sensor networks include (eg, Chong & Kumar [2003]):

- bandwidth constraints, since there is always a restriction on the volume of data that is allowed to be broadcast;
- energy constraints, particularly for miniature, stand-alone sensors;
- network management as nodes join and leave;
- network control and routing;
- collaborative information processing.

These are discussed in Section 3.3.

In the United States' Navy's Capabilities for the Navy After Next Innovation Game Loop 3, a toolkit of network-enabled systems was investigated in the context of littoral warfare in an attempt to quantify the benefits of network-centric operations [Legg & Knight 2000]. The objective of the Game was to break the will of the enemy by employing the various tools in a realistic scenario so that their utility could be assessed in comparison with both existing equipment and equipment that was going to be acquired in the near future. To provide a frame of reference, perfect connectivity and reliability were initially assumed, so that all data were available to all users requiring access to them. The available systems included unmanned vehicles of various sizes and capabilities, distributed sensors, distributed weapons and small, fast, manned surface vessels that were operated analogously to aircraft. The philosophy was that there would be a greater gain by utilising a large number of small, low cost vessels and devices than by persisting with the traditional US Navy model of having relatively few, high value units that need to invest significant (and possibly disproportionate) resources for self defence. Such exercises are valuable, as they permit the potential operational benefits of various systems to be determined, and allow users to decide which concepts are of most value prior to development.

The DSTO has had some first hand experience utilising a large UAV, Global Hawk, for surveillance and reconnaissance trials in conjunction with a manned system [Smith, Lingard, Fiebig & Stacy 2001]. Important issues raised as a consequence of this experience include the following:

- Users should think in terms of systems, rather than sensors. There is far more to consider than just the UAV's sensor payload, including interfacing the sensor output to the information infrastructure, data links, ground stations, manning issues, and tactics, techniques and procedures.

- UAVs require a significant number of support personnel. The vehicle itself is unmanned, but humans are responsible for it, and need to control and maintain it. There are also issues regarding the safe usage of UAVs in airspace shared by manned aircraft.
- The data link that is in place between the aircraft and its ground station is critical.

There is a great deal of potential for the application of sensor networks to the Tactical Land environment, but there are many challenges yet to be addressed.

2.4 Specialised Tracking Processes

The Kalman and extended Kalman filters [Bar-Shalom & Fortmann 1988] are used to combine sensor measurements with tracks in many real-world target tracking applications. These filters are adequate in many circumstances, and the Kalman filter is optimal (in a minimum mean square error sense, for example) when the target's motion is linear with Gaussian variations, and the measurements have Gaussian distributed errors. However, there are tracking situations where a Gaussian approximation to the target's kinematic uncertainty is inappropriate, and there are trackers that perform more accurately than the Kalman filter under these circumstances. Of particular interest is the particle filter concept [Ristic, Arulampalam & Gordon 2004*a*, Mallick, Maskell, Kirubarajan & Gordon 2002], which is capable of operating on any probability density function by approximating it with a collection of weighted samples that have a representative density.

An example showing the inadequacy of a Kalman filter is the problem of tracking with a hard constraint, as illustrated in Figure 3. Here, a flying target has an estimated height that is very small in comparison with the uncertainty in that estimate. (Measurements may have been made by a ground-based radar with poor elevation accuracy, say.) The location of the target is constrained by the ground, below which we know the target cannot exist. A Kalman filter represents the uncertainty as an ellipse which extends well beyond the ground level, so it will do a poor job of estimating the kinematics of the target in this example. It is quite possible that the estimated target height will be negative. A far more appropriate probability density function does not extend beyond the known constraint.

More generally, it is possible to track a target more accurately when the tracker can adequately incorporate knowledge of the possible behaviour of a target. Apart from the target's state estimate being more accurate, the state estimate's probability density will better reflect reality, so that predictions will be more accurate. Predictions may be important in the search for a lost target, for example, or to help distinguish between data that corresponds to the target and false alarms, which do not. A detailed example of tracking a ground target with a priori information is given in [Ristic, Arulampalam & Gordon 2004*b*] and is discussed below.

Particle filters may be used to deduce additional information about a target. Mallick et al. [2002], for example, discuss the tracking of targets in the littoral where a particle filter is used to perform both target tracking and classification tasks, that is, determining the probability of the target being land-based or sea surface-based. Far more elaborate classification is possible.

It is also possible to use particle filters to track targets that are difficult to detect, for example where they have a low radar cross section compared with the background clutter. The conventional approach to target tracking involves thresholding the data prior to associating measurements with tracks and updating a filter; an alternative is to use the tracker to integrate the raw data according

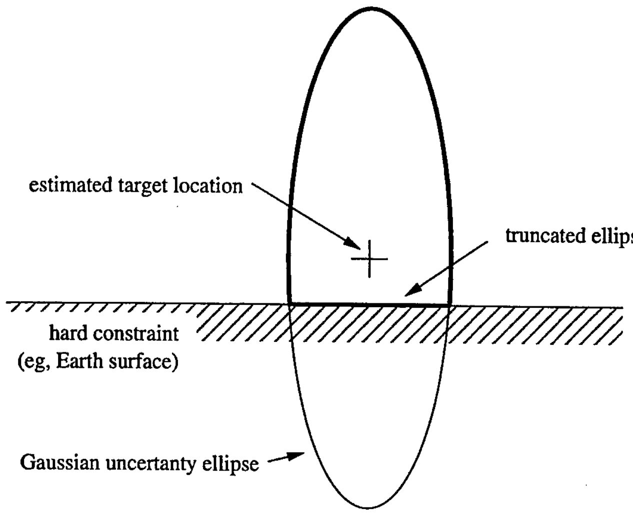


Figure 3: Tracking with a hard constraint.

to a model of the target's motion and determine the probability of existence of the target, as well as its kinematics. Rutten, Gordon & Maskell [2004] show an example of this using a particle filter (although the existence probability is erroneous in this paper[2]).

Although computationally intensive, owing to the large number of samples and weights that may need to be dealt with, it may be possible to implement particle filters using computing equipment that is modest by modern standards. For example, a particle filter that was used to track the location of a vehicle, based on a map and wheel position information, ran on a Personal Digital Assistant (PDA) [Gordon 2003]. The system did not require the Global Positioning System (GPS) as it was possible for the filter to deduce where on the map the vehicle was by correlating the motion of the vehicle with the roads shown on the map. The next section discusses a particle filter-based tracking application in more detail.

2.4.1 Ground Target Tracking with A Priori Terrain Information

Synthetic Aperture Radar (SAR) and Ground Moving Target Indication (GMTI) are important capabilities for wide area surveillance in the Land environment, providing imagery of the theatre, a picture of the disposition of moving ground vehicles and helicopters, and potentially providing the enemy force composition and intent [Entzminger, Jr., Fowler & Kenneally 1999]. The difficulty of dealing with land targets is far greater than that of air targets, owing to clutter and the slow moving nature of the targets of interest [Overman, Leahy, Lawrence & Fritsch 2000]. Synergistic SAR and GMTI may be available at a number of levels, from satellite-based systems that can provide relatively low resolution information within a short time frame, to large manned or unmanned aircraft that provide higher resolution over a smaller area, to tactical UAVs, which have the potential to provide detailed information regarding an area from a number of angles. To be of greatest utility, the data from such diverse systems need to be available seamlessly.

[2] Conversation with Neil Gordon, June 2004.

Interoperability of ground imaging and GMTI products is critical for the optimal utilisation of surveillance assets. The North Atlantic Treaty Organisation (NATO) has a Coalition Aerial Surveillance and Reconnaissance (CAESAR) programme that is directed towards improving the detection and tracking of ground vehicles using radars by developing the concept of operations, tactics, techniques and procedures, as well as the technology, in a coalition environment [Long 2001]. Platforms involved in trials include the US Joint Surveillance Target Attack Radar System (Joint STARS), the French Helicopter (HORIZON), the Italian CRESO, the UK Stand Off Radar, and the US Global Hawk UAV, U-2 and Predator UAV.

Ristic et al. [2004*b*] discuss the concept of tracking a ground vehicle using a sensor, such as a radar, and prior knowledge of the terrain, including the location of roads, intersections and tunnels. The assumption is that vehicles that are travelling along a road have a high probability of continuing to travel along that road, whereas vehicles that are off-road may travel in any direction. Other factors may be incorporated into the tracking process, such as prior knowledge of the performance of the target vehicle, and the coverage of the sensor, which may be affected by the terrain, such as obscuring hills and tunnels. It is shown, using simulated data, that it is possible to track the target far more accurately when such knowledge is incorporated into the tracking process than when it is ignored. Figure 4 shows an example scenario where a target travels cross-country to a road, through a tunnel, across an intersection, along another road and into a paddock[3]. Dotted lines denote regions where the vehicle is unable to enter or leave the road, such as where the road passes though a tunnel.

The conventional approach to this problem is to approximate the road constraints using a target motion model that is dependent upon the orientation of the section of road that the target is associated with. Although the uncertainty in the motion is still Gaussian, it is elliptical and oriented in line with the road. An interacting multiple model (IMM) framework [Blackman & Popoli 1999] can be used to account for the possibilities that the target may continue along a road, turn onto another road, depart from the road network altogether, and so on.

[3]The figures were borrowed from [Ristic et al. 2004*b*] with permission from one of the authors.

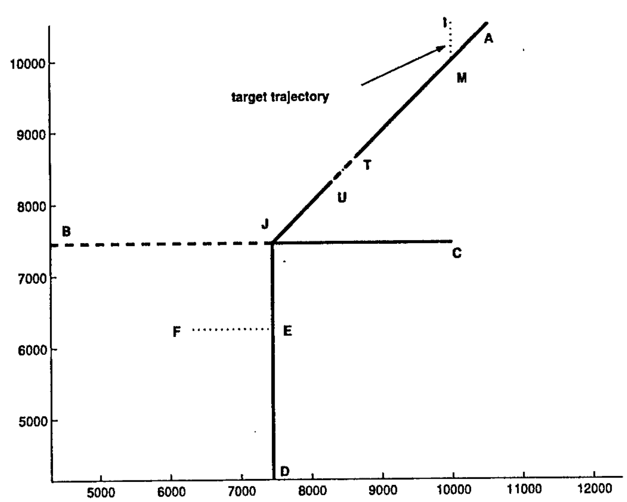


Figure 4: Terrain-aided tracking: the simulated target travels from I to F.

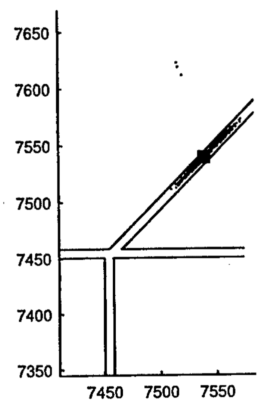
An alternative approach is to use a variable structure, interacting multiple model, particle filter (VS-IMMPF). Here a set of particles is used to represent the probability density function of the target's unknown state. Since there are numerous constraints on the target, this representation more accurately approximates the uncertainty than does a Gaussian distribution. The particles are updated at each time step to reflect the predicted motion of the target, which depends upon the terrain information and known properties of the vehicle, and any new sensor measurements that have taken place. Details are given in [Ristic et al. 2004*b*]. The results of a simulation are shown as snapshots in Figure 5.

In Figure 5(a), the target is shown on the road segment U–J. The uncertainty in its location is indicated by the cloud of particles, whose mean is indicated by a black square. Figure 5(b) shows the corresponding mode probabilities. Mode 0 corresponds to the target travelling off-road, and the other modes correspond to the different road segments. Clearly, there is a high probability that the target is travelling along road A–J. Figure 5(c) shows the target at intersection J. Owing to the uncertainty in the target's motion, the particles have been distributed along the various roads. This is reflected by the mode probabilities (Figure 5(d)). In Figure 5(e), the target has left the road and is in mode 0 (Figure 5(e)). The particles reveal that there is now considerable uncertainty in the motion of the target in all directions.

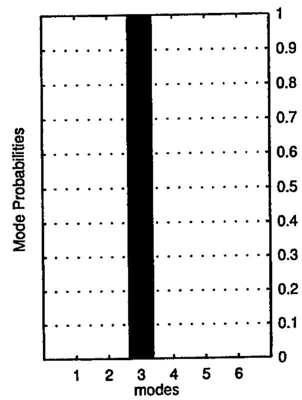
Figure 6 shows the error performance of the variable structure IMM (VS-IMM) and particle filter (VS-IMMPF) approaches. Performance is similar where the simulated target is off-road, where there are no hard constraints, but is significantly better in the particle filter case where the target follows a road. The uncertainty grows significantly in both cases where the target enters the tunnel owing to the loss of measurements from the sensor. Further gains are possible where additional knowledge regarding the motion of the target, such as its maximum speed, is taken into account.

The identity of the target may be inferred using techniques such as these. For example, the fact that a particular vehicle is associated with a particular road, railway line, sea lane or air lane at a particular time may suggest its identity. Further clues may be derived from a knowledge of its origin or destination. Gordon, Maskell & Kirubarajan [2002] discuss the use of particle filters for joint tracking and classification.

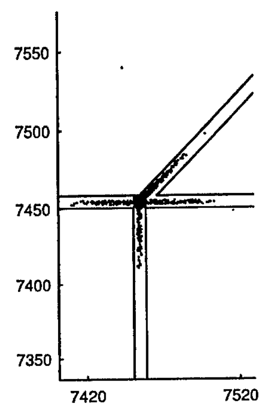
This example demonstrates the advantage of using prior knowledge in a tracking problem, and the utility of implementing a complex problem using an appropriate framework, rather than applying traditional techniques.



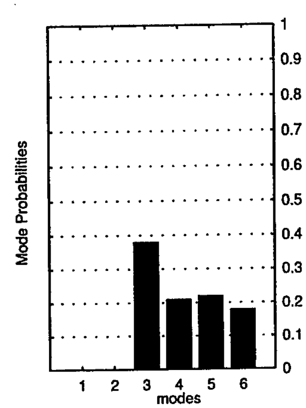
(a) Particle cloud at time $k = 68$; target in U–J.



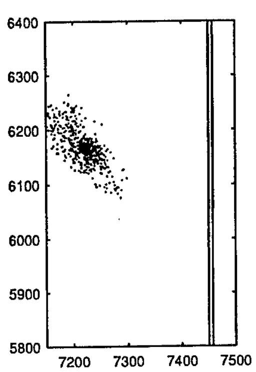
(b) Mode probabilities at time $k = 68$.



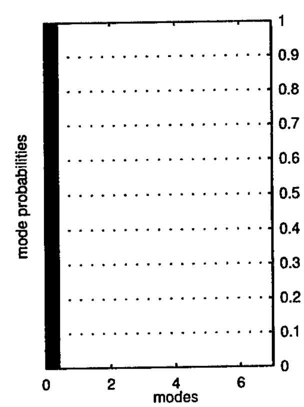
(c) Particle cloud at time $k = 70$; target at J.



(d) Mode probabilities at time $k = 70$.



(e) Particle cloud at time $k = 95$; target on E–F.



(f) Mode probabilities at time $k = 95$.

Figure 5: Snapshots of the terrain-aided tracking filter output.

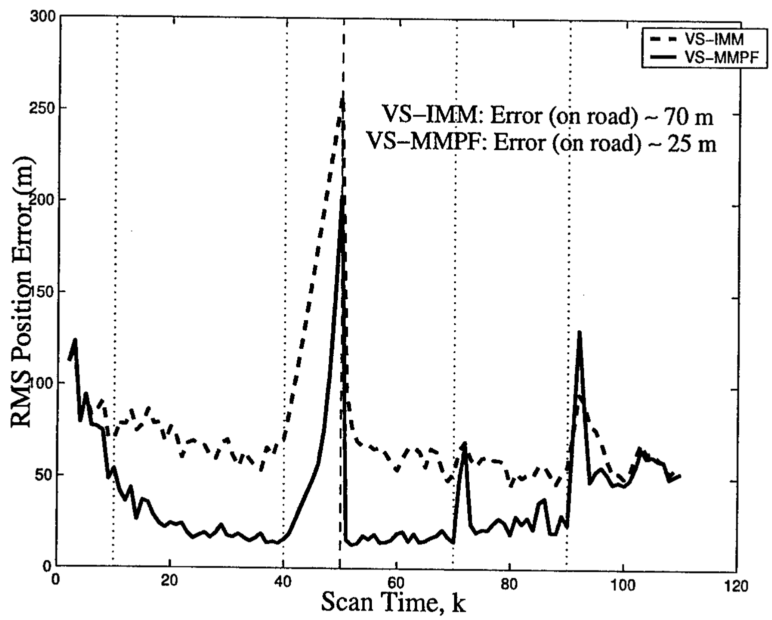


Figure 6: Tracking filter accuracy achieved using conventional (VS-IMM) and particle filter (VS-IMMPF) approaches.

3 Distributed, Multisensor Fusion Issues

This section discusses a number of issues that need to be addressed by systems that employ multiple, communicating sensors. These include picture consistency and track management, sensor registration, networking architectures and measures of performance.

3.1 Picture Consistency

At a high level, *picture consistency* is the degree to which commanders with access to different tactical pictures share a common situation awareness, and are able to make the same decisions[4]. This is particularly important when spatially separated decision makers, who are unable to access the same track database, need to agree on a course of action or act in concert.

This problem is illustrated in Figure 7. Any combination of sensors and communications links may be used to form the track databases that are presented as tactical pictures to the users. Although consistency between users' perception is of prime importance, this may be approximated in practice by consistency between the track databases and an appropriate human-machine interface (HMI). The databases may be manifested differently for each user, depending on the users' needs. For example, high accuracy may be important to a tactical user, but not to a strategic user. It is also important for these databases to represent the truth to within the stated uncertainty. This should follow when consistency is maintained.

[4]This section is based on previous studies performed in conjunction with Samuel Davey, Mark Krieg and John Percival.

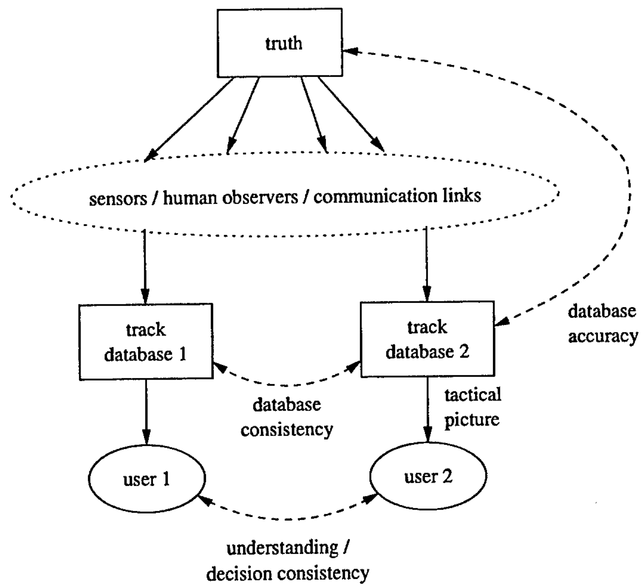


Figure 7: The picture consistency issue.

High level databases may be deemed consistent when there is a direct correspondence between the tracks in those databases; that is, it should be possible to relate each track in one database uniquely with a track in another. Corresponding tracks should have the same identifying number, and positions, velocities and characteristics that are only different to the extent that is consistent with their specified accuracies.

At a low level, where track databases in individual sensors are communicated to a system that fuses the data, the tracks in the higher level databases should be traceable to tracks in the sensor databases. When similar sensors are able to detect targets in the same region, consistency between their databases is expected to avoid ambiguity and conflict in the information presented to the user. However, for different types of sensors, it is not expected that there be complete consistency between their databases since their detection capability may be complementary. An example of this is the output from radar and IRST sensors, each of which may be capable of detecting targets in the other's region of clutter. Inconsistency between two databases occurs when they contain information that cannot be explained by making approximations to the lower quality database.

Maintaining consistency is relatively straightforward at low levels of sensor fusion, where consistency is well defined and algorithms are capable of performing the task, albeit with some degree of operator input. This extends to the use of a Tactical Digital Information Link (TADIL) to maintain a situation awareness picture between combat systems on different platforms, for example. At higher levels of information fusion, where information products are more abstract in nature, consistency is more difficult to define, and it is expected that operators are required to resolve conflicts.

It may be possible to implement a distributed sensor fusion system using architectural features that help prevent picture inconsistencies. An example of such a feature is where a radar's tracker contributes to a global track database that is also updated by other local or remote sensors. Inconsistencies may be avoided by feeding the global tracks from this database back to the radar's

tracker, which can use them when associating local radar measurements with existing tracks. In this way, there is less room for ambiguity than if the radar uses its local data for measurement association. Sensor registration may also be performed locally by the radar's tracker in this case.

3.2 Sensor Registration

In order for the data from different sensors to be successfully combined to produce a consistent product, the sensor data need to be correctly registered. That is, the relative locations of the sensors, the relationship between their coordinate systems, and any timing errors need to be known, or estimated, and accounted for. Failing to correctly account for registration errors may result in a mismatch between the compiled picture and the truth, an overstated confidence in the accuracy of the fused output, and inconsistencies between track databases, such as multiple tracks that correspond to a single target.

Misregistration can result from location and orientation errors of the sensor relative to the supporting platform, or of the platform relative to the Earth, such as a bearing measurement with an incorrect north alignment. Errors may be present in data time stamping, and numerical errors may occur in transforming data from one coordinate system to another. Automatic sensor registration, or "gridlocking", can correct for these problems by estimating the bias in the measurements along with the kinematics of the target. However, the errors in sensor registration need to be known and accounted for. Performance bounds for sensor registration are discussed by Gordon, Ristic & Robinson [2003].

3.3 Network Management

There are many ways in which a collection of distributed sensors may be managed, and their appropriateness depends upon the application. However, there generally need to be algorithms and protocols in place for managing aspects including [Chong & Kumar 2003, Legg 2004]:

Network discovery. Since the organisation of nodes in ad hoc networks is unknown a priori, the nodes need to determine which of the other nodes they need to communicate with in real time, as participants join and leave the network. This is particularly true in the Tactical Land environment, where communications may be dynamically blocked by terrain, and sensors or vehicles may be added at arbitrary times. Absolute or relative sensor locations and orientations also need to be known so that data may be compared and combined.

Picture consistency. As discussed in Section 3.1, maintaining picture consistency is an important consideration for network design and management, particularly in an environment where distributed sensors may need to minimise transmissions and have variable overlaps in their areas of coverage. Standards need to be established for representing tracks, including uncertainties and target motion models. Procedures for track association, track merging, track divergence and the assignment of track numbers may need to be defined. Mechanisms need to be in place to resolve conflicts.

Network control and routing. Resources, such as energy and bandwidth, need to be managed so as to provide robustness and reliability in the communications infrastructure as data links

form and fade. Standard mechanisms such as Internet Protocols (IPs) are inappropriate in a constrained, dynamic environment where static node addressing cannot be assumed. There may be latencies between sensor measurements and the corresponding data becoming available to other nodes via the network. These may be variable, and data may arrive out-of-sequence. The network should be scalable, meaning that additional sensors should improve performance, rather than just increase the resources required to operate the network.

Collaborative signal and information processing. There are tradeoffs between communicating low level data and providing local processing to reduce the volume of data that needs to be broadcast. Sensor fusion algorithms need to be appropriate for the estimation task and the available resources. For example, is a Gaussian assumption reasonable, meaning that a Kalman filter-based algorithm is adequate, or do we have the resources to implement particle filters? Processing nodes may also need to be aware of the data's pedigree so as to avoid the reuse of data. An information-driven approach to sensor collaboration is discussed in [Zhao, Shin & Reich 2002].

Tasking and querying. Sensor tasking may be determined via prior planning and/or automated, dynamic resource allocation, such as for a radar frequently revisiting a high priority target for track updates. There may also be means for the automatic cueing of sensors.

The goal of having a simple user interface for the data fusion system may be a challenge, since the database is distributed, updated dynamically, and its interpretation necessitates an appreciation of the uncertainties in the data. It must also be possible for the user to view the raw data that led to a fusion output.

Security. There should be protection from intrusion and spoofing. It is important that the integrity of the network is maintained.

Correctly specifying the Measures of Performance (MOPs) is critical for the meaningful assessment of a tracking or sensor fusion system. There are many possible MOPs, and they may be categorised according to track establishment (such as the establishment delay and the number of omitted tracks), track maintenance (including the missed target history, number of divergent outbreaks, and the number of track association changes), tracking error (such as the position, heading and speed errors) and false tracks (in particular, the false track rate and false track length) [Colegrove, Cheung & Davey 2003]. It is possible to form weighted sums of the metrics to determine the overall performance of a tracking system for a particular application. MOPs are quantifiable, and should contribute to higher level Measures of Effectiveness (MOEs) and Measures of Force Effectiveness (MOFEs) [Hall & Llinas 2001].

4 Manual Observers

Although much effort in modern surveillance systems is directed towards the automatic detection and tracking of targets, manual observers play an important role in the Tactical Land environment. Sensors, such as radars, may not be very portable, may perform poorly under high clutter conditions, and may suffer from terrain obscuration owing to hills, buildings, etc. It may also be necessary for surveillance to occur covertly, so that emissions from active sensors, such as radars, are to be avoided.

Bergman & Sviestins [2003] discuss the incorporation of reports from manual observers, along with reports from sensors such as radars, into a Saab Technologies commercial tracking system. Characteristics of manual observers and their reports include

- utility in difficult conditions such as urban environments,
- difficulty of jamming,
- a low false alarm rate,
- limited coverage,
- large location errors that are not Gaussian distributed, and so are not properly utilised by a conventional (Kalman) tracking filter,
- variable report delays (up to a minute seen by Bergman & Sviestins [2003], with type information arriving 10–30 s later than corresponding kinematic information), and
- out-of-sequence information.

This author also anticipates a high target detection probability, particularly at short range to the observer, and very accurate and reliable identification information.

A manual observer's report may include any or all of: target direction, target distance, target heading, whether or not the target has been reported previously, target affiliation (friendly / hostile / neutral), target size, and target type (according to ten categories in [Bergman & Sviestins 2003]). Registration of manual reports may be a problem (although this was not investigated in [Bergman & Sviestins 2003]).

Bergman & Sviestins [2003] modelled manual reports as being Gaussian but non-linearly quantised in range ("close", "near" and "far") and altitude ("very low", "low" and "high"). Ad hoc methods were used to update existing tracks using the reports to avoid forcing the track output towards the mean of the quantised steps. The target bearing accuracy was estimated using the assumption that the observer used binoculars.

Owing to the presumed reliability of the observers, that is, a low false alarm rate, tracks were initiated using very few reports. This was especially the case if the reports had a "close" range. However, tracks initiated by observer reports had a very high kinematic uncertainty.

The process of associating observer reports with existing tracks was complicated by the variable delays of kinematic and type information. However, it was concluded that the integration of the manual reports into the commercial tracker was straightforward and successful, although the performance had not been thoroughly evaluated.

It is anticipated that the incorporation of manual identification information into existing track data would be very valuable, and that manual reports may potentially be useful for sensor cueing[5]. Possible extensions to [Bergman & Sviestins 2003] are to allow the tasking of the observer and then incorporating negative information if nothing is reported[6], and to better model the report probability density functions so that more accurate tracking may be achieved.

[5] Conversation with Dr Mark Krieg, June 2004.

[6] Conversation with Dr Neil Gordon, December 2003.

5 Conclusions

In comparison with the air and sea environments, situation awareness in the Tactical Land environment is complex and demanding owing to sensors' restricted fields of view, limited access to resources such as power, and the difficulty in distinguishing between objects of interest and the surrounding clutter.

Improvements in situation awareness may result from the utilisation of systems such as networks of distributed sensors, which should be able to conduct reliable surveillance over tactically useful areas using little power, and the appropriate processing and dissemination of the data that are available from all sources, including sensors and databases. However, sensor processing and data fusion are complex, and problems such as sensor registration, network communications and sensor management are far from being properly solved.

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